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Investigation of Methods to Produce a Uniform Cloud of Fuel Particles in a Flame Tube

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SUMMARY

The combustion of a uniform, quiescent cloud of 30-μm fuel particles in a flame tube has been proposed as a space-based, low-gravity experiment. The subject of this report is the normal- and low-gravity testing of several methods to produce such a cloud, including telescoping propeller fans, air pumps, axial and quadrature acoustical speakers, and combinations of these devices. When operated in steady state, none of the methods produced an acceptably uniform cloud (±5 percent of the mean concentration), and voids in the cloud were clearly visible. In some cases, severe particle agglomeration was observed; however, these clusters could be broken apart by a short acoustic burst from an axially in-line speaker. Analyses and experiments reported elsewhere (briefly summarized herein) suggest that transient, acoustic mixing methods can enhance cloud uniformity while minimizing particle agglomeration.

INTRODUCTION

The NASA Lewis Research Center, in conjunction with universities and private industry, is currently conducting analytical studies and conducting experimental normal- and low-gravity combustion research. One area of interest is combustible particle clouds. Scientific knowledge of the characteristics of particle-cloud combustion could contribute to the control of fire and explosions in underground mining operations, and grain storage and handling facilities. The more salient characteristics of scientific interest deal with flame structure, propagation rates, stability limits, and the effects of stoichiometry, particle type, transport phenomena, and nonadiabatic processes (ref. 1).

Premixed-gas combustion experiments and particle-cloud combustion experiments are conducted similarly. The combustion chamber is a 5-cm-diam, 100-cm-long, transparent flame tube with one open and one sealed end. The fuel and oxidizer are mixed in the flame tube and, then, are ignited at the open end; the flame is observed as it propagates. One major difference between premixed-gas and particle-cloud combustion studies in normal gravity

is that the gas can achieve a state of uniformity and quiescence before ignition, whereas the particles settling out in normal gravity prevent quiescence in the cloud. To achieve the quiescence that is characteristic of the classical premixed-gas studies, a low-gravity experiment was conceived; the longer particles settling time in low gravity might provide an acceptable degree of quiescence prior to and during flame spread.

An investigation was conducted for a process that would mix the particle fuel to specified uniformity requirements in a flame tube in a low-gravity environment. Tests performed for a ground-based feasibility study led to the conclusion that a concentration uniformity of ±10 percent from the mean could be achieved with some regularity for fuel-rich mixtures (ref. 1). The hardware configuration was a single-axial acoustic speaker mounted on a 63.5-cm flame tube in a horizontal position; the fuel was spread along the bottom side of the tube. This mixing method is being used in a ground-based research program being conducted in the drop towers and the Learjet.

The initial position of the fuel inside the flame tube is very important to this method, and maintaining the fuel in a known, initial position from the time the fuel is loaded until the experiment is performed demands precise control over the experiment package. This control is possible with ground-based experimentation, but it may be impossible for experiments flown aboard the shuttle, because of the varying gravity levels acting on the shuttle during launch and orbit operations. The short duration of the low-gravity environment in drop towers or the Learjet does not permit a repetition of the mixing process to achieve a particle cloud within uniformity limits. This limitation on mixing is not a serious handicap for the ground-based research testing; however, the capability to repeat the mixing process is a desirable feature for a space flight experiment, since no provision was made for changeout of the flame tube. Furthermore, a space-based experiment allows long mixing times, and a mixing method could require a longer period than available in ground-based facilities, particularly if the initial particle position is highly nonuniform or unknown.

A mixing method that is independent of initial fuel position was sought for use in space experiments. The following mixing methods were investigated and tested: (1) a single axial speaker, (2) twin axial speakers, (3) quadrature acoustic drivers, (4) a fan, (5) an air pump, (6) a plunger, and (7) a fan and speaker combination. The test configurations, the experimental procedures, and the test results are described in this report and a pictorial summary is given in tables I and II.

SINGLE AXIAL SPEAKER METHOD

This section summarizes the results (ref. 2) of mixing fuel and oxidizer in a flame tube by using a single axial acoustic speaker. These results provide a baseline for a comparison of the other methods investigated.

Test Configuration

The test configuration of a flame tube with some of the associated hardware is shown in figure 1. The flame tubes were 25, 63.5, and 75 cm long and 5 cm in diam. Some of the flame tubes had an expanded section at one end that

was 10 cm long and 6 cm in diam. Aluminized Mylar (Dupont) diaphragms, 0.01-mm-thick, capped each end of the flame tube to contain the fuel during the mixing operation.

On one end of the flame tube, an acoustic speaker was mounted. The speakers were rated from 5 to 30 W with operating frequencies ranging from 55 to 5000 Hz. The diameter of the speakers was 10.2 cm, and the dc resistance was 8 Ω. On the end of the tube opposite the speaker were an igniter, a heat sink, and an exhaust bag. Once the fuel was mixed, the igniter provided the energy to initiate combustion, and the heat sink cooled the exhaust gases, which were contained by the exhaust bag. Mixing sensors, consisting of light-emitting diodes and photocell detectors, used light attenuation to determine fuel concentration.

High-speed photography and video equipment were used to record the mixing action obtained during the various tests. Photography was done with 16-mm film operated at 400 frames/sec. The video recordings were made at 30 frames/sec.

Testing in Low Gravity with Vertical and Horizontal Flame Tubes

A series of tests were conducted in the 2.2-sec drop tower with the 75-cm flame tube in a vertical position. In the vertical position, the fuel was always at the bottom. For some of the tests, the acoustic speaker was at the bottom of the tube, and for others, on the top of the tube. After observing the mixing action, a decision was made to increase the duration of the low-gravity environment from 2.2 to 20 sec by conducting these tests in the Learjet. After several tests of the mixing action in vertical tubes, a series of tests were conducted with the tube in a horizontal position. In the latter case, the fuel could be positioned at locations other than on the diaphragms, thereby, allowing investigation of the effects of such random positioning.

Diaphragm Tests

A series of normal-gravity tests were conducted to study the effects of diaphragm tension on the mixing process. The diaphragm tension was categorized by measuring the deflection of the diaphragm when an 8.3-g steel ball was placed in the center of the diaphragm (ref. 2).

The experiment was conducted in a vertical flame tube, with the speaker on the bottom and the fuel on the bottom diaphragm. When the speaker was energized, a cloud rose and remained suspended, but only in the lower portion of the flame tube. The cloud achieved its greatest height when the diaphragms at both ends of the tube were loose (diaphragm deflects 0.32 cm). And for a given pair of diaphragms, the cloud rose highest when the looser diaphragm was closest to the speaker. During testing, variation in the tension of the diaphragms was seen to affect both the degree of agitation and the ability to move the suspended cloud throughout the flame tube. With tight diaphragms, some axial movement of the fuel cloud was achieved by slightly varying the speaker frequency; however, this axial movement could not be achieved with loose diaphragms.

Results and Conclusions

Whether the speaker was on the top or the bottom of the vertical flame tube, a continuously rising cloudlike formation of particles was produced in both normal and low gravity. This formation would nearly reach the midpoint of the flame tube while the experiment package completed the 2.2-sec low-gravity drop.

When the vertical-flame-tube tests were repeated in the Learjet, the cloud rose to slightly higher than the midpoint of the flame tube (51 cm rather than 38 cm). But the cloudlike formation did not fill the entire flame tube during the longer low-gravity test.

Except for one method, that is, with flame tube in the horizontal position with the fuel at various locations, achieving a visually acceptable uniform cloud of fuel throughout the entire flame tube was not possible for any of the mixing times used. Also, the fuel was noted to have a tendency to move away from the speaker during the mixing operation.

The procedure for the one method that achieved fuel clouds with a uniformity of ±10 percent is as follows: (1) The flame tube was placed in a horizontal position; (2) The fuel was spread evenly along the bottom of the flame tube in a 0.5- to 1.0-cm wide row; and (3) after the flame tube entered a low-gravity environment, the acoustic speaker was energized for a period of less than 1 sec. A cloud filled the entire length of the flame tube. This mixing method was selected for ground-based testing in the 2.2-sec drop tower and in the Learjet; some of these results have been reported in reference 1.

TWIN SPEAKERS

This section summarizes the fuel mixing in a flame tube by using twin axial acoustic speakers, for which only normal-gravity testing was performed.

Test Configuration and Normal-Gravity Tests

During fuel mixing tests using a horizontal flame tube with a single axial acoustic speaker, a tendency was observed for the fuel to move away from the speaker as the duration of the speaker operation increased. From this observation, a configuration with an axial acoustic speaker mounted on each end of the flame tube (fig. 2) was developed . A T-section inserted between one end of the flame tube and the speaker at the igniter provided a path for the products of combustion to enter the exhaust bag. The T-section was 15 cm long; the speakers were rated at 17 W and were operated at 15 W output. The fuel location was random for these tests.

Speaker B was located on the igniter end of the flame tube and speaker A, on the opposite end. Four different tests were performed. During each of the four tests, the operating frequency for speaker A was 150 Hz, and that for speaker B was 155 Hz. For the first test, speaker A was on continuously, and speaker B was turned on and off at the rate of 1/2 to 1 Hz.

For the second test, speaker A was turned on and off at 1/2 to 1 Hz, and speaker B was on continuously. For the third test, both speakers were alternately turned on and off at a rate of 1/2 to 1 Hz (i.e., when speaker A was on, speaker B was off, and when speaker B was on, speaker A was off). For the fourth test, both speakers were on continuously, with a phase angle of 0° or 180°. The phase angle did not have a noticeable effect on the cloud uniformity created by the mixing method.

Results and Conclusions

The twin speaker configuration was tested only at normal gravity with the flame tube in a horizontal position. The results for the first and second tests were similar. With one speaker on continuously, a cloud of fuel formed near the center of the tube. The cloud length was about one-quarter of the length of the flame tube. During the test, the cloud slowly drifted away from the speaker that operated continuously. Cycling the second speaker on and off caused a momentary interruption of the slow drift of the fuel cloud and produced a vertical rise of the fuel in the riblike structure associated with a flow transient, as noted in references 3 and 4.

As one speaker was turned on and the other turned off in the third test, the response of the fuel to the on-and-off cycles was the same as previously noted. The fuel would rise and be pushed away from the speaker that was turned on. As the test progressed, most of the fuel was located in the middle third of the flame tube, and it was tossed left and right in rhythm with the operating sequence of the speakers.

During the fourth test, the length of the fuel cloud was about one-quarter the length of the flame tube. The cloud drifted slowly toward speaker A. During this test, a uniform cloud was not observed anywhere in the flame tube. As the operation of the speakers continued beyond 1 sec, the fuel near the speakers was significantly depleted. The test results from this configuration indicated a low probability of successfully obtaining a uniform cloud of fuel throughout the entire flame tube.

QUADRATURE ACOUSTIC DRIVERS

This section summarizes the results (ref. 5) of acoustic mixing experiments in a flame tube by using frequency spinning modes produced by quadrature acoustic drivers. All experiments were performed in normal gravity.

Test Configuration and Test Results

The basic experimental setup and the hardware specifications for quadrature acoustic drivers are shown in figure 3 and appendix A respectively. The quadrature acoustic driver setup is designed to excite slow axial-moving, spinning waves (fig. 4) by using two phased-controlled acoustic drivers mounted at a 90° angle from each other with their axes in the same cross-sectional plane. A set of wall-mounted, axial and radial microphone probes allows identification of the three-dimensional sound field inside the flame tube. In some experiments, a low-frequency axial speaker was mounted at one end of the flame tube. Figure 5 shows the various experimental configurations investigated. The fuel was distributed along the entire length of the flame tube.

Quadrature mixing (fig. 5(a)) produced circumferential circulation of the fuel around the inside of the flame tube. Strong particle motion was observed in some sections of the tube, but circulation was limited to about one-third of the flame tube length. Specific details about the experimental setup and the theory are given in reference 5.

Quadrature Acoustic Drivers and Axial Speakers Test Results

Simultaneous operation of the quadrature acoustic drivers and the axial speaker (fig. 5(b) and (c)) produces considerably enhanced motion, compared to the operation of the quadrature acoustic drivers alone. A strong circumferential circulation of the fuel occurred over about two-thirds of the flame-tube length with either of the experimental configurations shown in figure 5, parts (b) and (c). Fuel particles in the remaining one-third of the flame tube did not form a cloud. Mixing experiments that used the quadrature acoustic drivers and axial speaker showed much less longitudinal fuel drift than was observed in experiments that used an axial speaker alone (ref. 5).

Other Configuration Test Results

Several other configurations were tested in an effort to increase the homogeneity of the cloud. Figure 5(d) shows quadrature acoustic driver sets mounted on each end of a flame tube. Only a few combinations of phase angles and amplitudes between the acoustic drivers were tried, and since no substantial improvement over previous configurations was observed, no further work was done using this setup.

Another experiment was conducted with an anechoic termination (fig. 5(e)) that was designed to eliminate reflection of the sound field in the flame tube. A strong longitudinal fuel drift away from the sound source prevented any satisfactory mixing.

Conclusions

The greatest fuel motion was obtained by using a combination of quadrature acoustic drivers and an axial speaker. Both the experiments and the theoretical analysis indicate that acoustic transients are more likely to produce acceptable mixing than are steady-state conditions, because in steady conditions flow structures, like nodal planes, separate the mixing region into cells across which fuel cannot be transferred. Transients are not only free of such structures, but they also have the characteristics of randomness and disorder, which are desirable for mixing. This conclusion was corroborated by using axial waves in mixing experiments.

FANS

Two types of fan configurations were tested during the alternate mixing investigation. The first configuration employed a fan external to the flame tube (fig. 6). The fan and housing were attached to one end of the flame

tube, and a return path for the circulating air was provided from the opposite end of the flame tube back to the fan. This configuration was tested in normal gravity only. The second configuration had a miniature fan inside the flame tube. The fan was attached to a moveable rod (fig. 7) so that the fan could be moved axially along the length of the flame tube. Both normal- and low-gravity tests were performed with the second configuration. The low-gravity tests with fans inside the flame tube were performed in combination with acoustic speakers; the results are reported in the section Fan and Speaker Tests.

External Fan

Test configuration. - The external fan test configuration with a horizontal flame tube is shown in figure 6. At the igniter end of the flame tube, a large-diameter housing enclosed an axial-flow fan driven by an electric motor. The inlet side of the fan housing was connected to a 5.0-cm-diam copper tube that loops around and connects to the opposite end of the flame tube. When the fan was operated, a continuous flow of air moved through the flame tube and continued through the copper tubing back to the inlet side of the fan.

Initially, 1 g of lycopodium was spread evenly along the length of the horizontal flame tube. The unducted fan was rated by the manufacturer at 3.4 m^3/min with the motor operating at 3400 rpm.

Normal-gravity results and conclusions. - During the fan startup, the fuel particles moved in a spiral flow pattern from the igniter end of the flame tube toward the opposite end. At midlength of the flame tube, the fuel particles either fell or adhered to the inside wall surface of the flame tube. Beyond this point, no fuel particles were airborne. The mechanism for adhesion was attributed to electrostatic attraction between the fuel particles and the flame tube material, Lexan (General Electric Co.) (ref. 6). Further tests were not conducted.

Internal Fan

Test configuration. - Three miniature axial-flow fans of different sizes and power ratings were used to conduct this investigation. The first fan (Micronel, model V481L) was 4.8 cm in diam with an electrical power rating of 4.2 W at 24 V; the second (Micronel, model V301L) was 3.0 cm in diam with an electrical power rating of 0.84 W at 24 V; and the third fan (Micronel, model V241L) was 2.4 cm in diam with an electrical power rating of 0.3 W at 12 V.

One test configuration consisted of the 4.8-cm-diam fan operated at 9 V in a 75-cm-long flame tube. As the fan was moved axially along the length of the tube, the fuel moved along the flame tube. When the fan approached the end of the flame tube (about 12 cm from the end), the fuel ceased to move along the flame tube; instead it formed a pile in front of the fan. At no time during the test did the fuel form a cloud in the flame tube.

Normal-gravity test results. - Normal-gravity tests for different combinations of variables were conducted in 25- and 75-cm-long flame tubes. The fans were operated to obtain forward and reverse flows of air, with and without the

blade cowling, at different axial locations on and off the centerline in the flame tubes and at different power settings.

The mixing action achieved in the flame tube by the various configurations was about the same except for when the electrical power to the fans was varied. As electrical power to the fan was increased, the fuel agitation increased, and more fuel was moved down the flame tube; however, a cloud was not formed.

AIR PUMP MIXING

This mixing method attempted to produce a uniform cloud of fuel particles in a flame tube by oscillating the air column in the flame tube with an air pump.

Test Configuration and Normal-Gravity Tests

The 75-cm-long, 5-cm-diam flame tube was mounted in pillow blocks that were bolted to a 0.64-cm-thick, 122- by 79-cm aluminum plate, as shown in figure 8. The plate was bolted to a heavy steel workbench. A modified pneumatic cylinder was connected to the flame tube by 2.54-cm PVC pipe. The pneumatic cylinder, which had a double-acting piston with a 5-cm stroke, oscillated the air column. A crank connected the 1/2-hp dc motor to the cylinder piston rod. The motor speed was varied from 0 to 1750 rpm with a manually operated speed controller. A description of the electrical controls and systems can be found in appendix B. The flanged end caps were used to mount 10- and 5-μm filter paper that not only contained the fuel in the flame tube but also allowed air to be pumped in and out of the 2.54-cm-diam PVC pipe.

Fuel was evenly distributed over the interior length of the flame tube at the beginning of each test. The filters were installed, the flanged end caps were assembled, and all the remaining fittings in the air lines were tightened. The tests were recorded on video tape and on high-speed film with a frame rate of 400 frames/sec. Initially, the pump was brought to about 50-percent speed, and the high-speed camera was started. Next, the motor that was driving the pump was rapidly accelerated to 1750 rpm and then stopped when a cloud formed. The high-speed camera was stopped when the particles settled to bottom of the flame tube.

The first checkout tests were performed with 10-μm filters, but they deteriorated after a few trial runs - becoming porous enough for the fuel to leak out of the flame tube and into the return piping and pump. The 5-μm filter paper corrected this problem.

The configuration of the filters and the blockage at the flame-tube inlet and exhaust ends were altered somewhat to add turbulence to the flow. Figure 9 shows the four configurations used. The same configuration was used at both ends of the flame tube for each respective test performed.

Results and Conclusions

The air pump mixing method produced a fuel cloud in the flame tube by oscillating the air column at a rate of 30 cycles/sec over a distance of 5 cm/per stroke in a 5-cm-diam flame tube. However, the cloud was not uniform throughout the length of the flame tube. At both ends of the tube the fuel particles became sparse after a few seconds of pumping. During each test most of the fuel cloud formed short, cylindrical segments of high and low density (fig. 10 shows a typical cloud formation). The uniformity of the fuel cloud was not improved by inserting the screens and blockages shown in figure 9 into the flame tube.

PLUNGER METHOD

This section summarizes fuel mixing in a flame tube by using a plunger.

Test Configuration and Test Results

The plunger method test configuration consisted of a 75-cm-long by 5-cm-diam flame tube with a mixing plunger, having air passages as shown in figure 11, that was attached to a 0.16-cm-diam rod. The rapid movement of the mixing plunger back and forth in the flame tube produced a turbulent motion of air and caused the fuel to mix. For both the normal-gravity and low-gravity tests, the mixing plunger was operated manually.

For the normal-gravity test, 600 mg of fuel was spread evenly over 38 cm of the flame tube. High-speed photography recorded the generation of a very turbulent particle cloud when the plunger was drawn over the length of the tube in about 1 sec. No attempt was made to push the plunger in the opposite direction. The particles then quickly fell to the bottom of the flame tube.

For the low-gravity tests, 1000 mg of fuel was spread evenly over 38 cm of the flame tube. High-speed photography recorded the generation of particle motion when the plunger was drawn over the length of the tube at a velocity of 25 to 38 cm/sec. The plunger was returned to the starting position, and the plunger motion was repeated.

In low-gravity testing, the particles became airborne in a nonuniform turbulent cloud, but unlike those in the normal gravity tests, they immediately agglomerated into clusters of particles.

FAN AND SPEAKER COMBINATION

This section summarizes the fuel mixing in a flame tube by using a fan and speaker combination in normal gravity and in low gravity.

Test Configuration and Tests

Fan and speaker combination tests were conducted in normal gravity in 25- and 75-cm flame tubes by using a 3.0-cm-diam 0.84 W fan with exposed blades

at 24 V. The fan was mounted at one end of the flame tube, and a midrange Realistic 5-W speaker was at the opposite end (fig. 12). The low-gravity tests were conducted in 25-cm flame tubes only.

Three sequences of fan and speaker combinations were tested in normal gravity and in low gravity. For the first test sequence, the fan was turned on for 1/2 sec; then 1/2 sec, after it was turned off, the speaker was turned on for 1/2 sec. For the second test, four 1/2-sec periods occurred in the following sequence: speaker on; speaker off; fan on; and fan off. For the third test sequence, the fan and speaker were turned on together for 1.5 sec and turned off together. For all tests the fuel was spread evenly over the length of the flame tube.

Results and Conclusions

Normal-gravity tests. - In normal-gravity tests with the fan on first, a small amount of fuel was swirled down the flame tube and settled out before the speaker system was turned on. When the speaker was turned on first, and then turned off, the powder settled out before the fan was activated. When the fan and speaker were operated simultaneously, a cloud was generated by the speaker, and the fan was able to move the fuel toward the speaker end. The fan by itself was not able to move a significant amount of fuel; however, once the fuel was airborne by the action of the speaker, the fan was able to move the fuel. When tests were conducted with only the axial speaker operating, there was a gradual movement of the fuel away from the speaker. When the speaker was operated with the fan, then the fuel was moved toward the speaker.

Low-gravity tests. - The normal-gravity test sequences were repeated in the 2.2 sec drop tower in a low-gravity environment. For the sequence of fan on and off and then the speaker on and off, the amount of fuel mixing was about the same as that observed in the normal-gravity tests.

For the second sequence, the speaker on and off and then the fan on and off, the fuel was still airborne when the fan was turned on, and there was a greater swirling action of the fuel toward the speaker end. More fuel agitation was evident in the low-gravity test than in the normal-gravity test.

The third sequence, the simultaneous operation of the fan and the speakers, resulted in a vigorous spiraling of the fuel towards the speaker. The spiraling was more pronounced than in the corresponding normal-gravity test.

One additional observation noted during the low-gravity testing was the reaction of agglomerated fuel particles to the acoustic energy. In one of the test sequences when the fan was turned on first, an agglomeration of particles formed near the middle of the flame tube. When the speaker was turned on, the agglomerated particles very rapidly broke up into individual particles.

These various fan and speaker operating sequences failed to produce a uniform cloud of fuel throughout the flame tube. In the low-gravity tests, the uniformity achieved by the speaker was always destroyed by the swirling action of the fan.

CONCLUDING REMARKS

The combustion of a uniform, quiescent cloud of 30-μm fuel particles in a flame tube has been proposed as a space-based experiment. In this investigation several methods of producing such a cloud were tested in normal- and reduced-gravity. A method was sought that could produce an acceptable uniform cloud (±5 percent of the mean concentration) in reduced gravity and that was independent of the initial fuel particle position. In addition a method that could be repeated if the first attempt at cloud formation was less than acceptable was desired. In normal gravity, 10 different methods, with 4 to 5 variations per method, were tried; the 4 most promising methods, selected on the basis of the normal-gravity test, were investigated further in low gravity. The test methods, variations, and results are displayed herein. None of the methods produced an acceptable cloud, because of undesirable axial migration of particles, agglomeration of airborne particles into large clusters, and/or lack of cloud formation in portions of the tube. These airborne particle clusters were broken apart by a brief acoustic burst.

Several of the mixing methods investigated were based on steady-state operation of the mixing devices (fan, speakers, and air pumps). Analyses and experiments reported elsewhere (briefly summarized in this report) suggest that transient operation, rather than steady-state operation, can enhance particle-cloud uniformity while minimizing particle agglomeration.

ACKNOWLEDGMENTS

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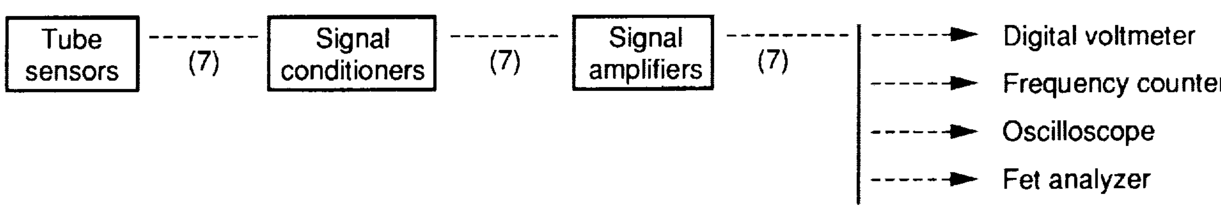
APPENDIX A

QUADRATURE SPEAKER MIXING METHOD TEST EQUIPMENT

Test instrumentation:

(1) Endevco pressure transducer (quantity 7), series 8510B, 5 psig
(2) Fluke digital voltmeter, model 8840
(3) Fluke counter/timer, model 1953A
(4) Tektronix oscilloscope, model 7704A; amplifier plug-in, model 7A26; time base plug-in, model 7B15
(5) PPM Inc. signal conditioner (quantity 7), model SG11-D1
(9) Preston Scientific signal amplifiers (quantity 7), model 8300
(10) Hewlett-Packard Spectrum analyzer, model 3580A

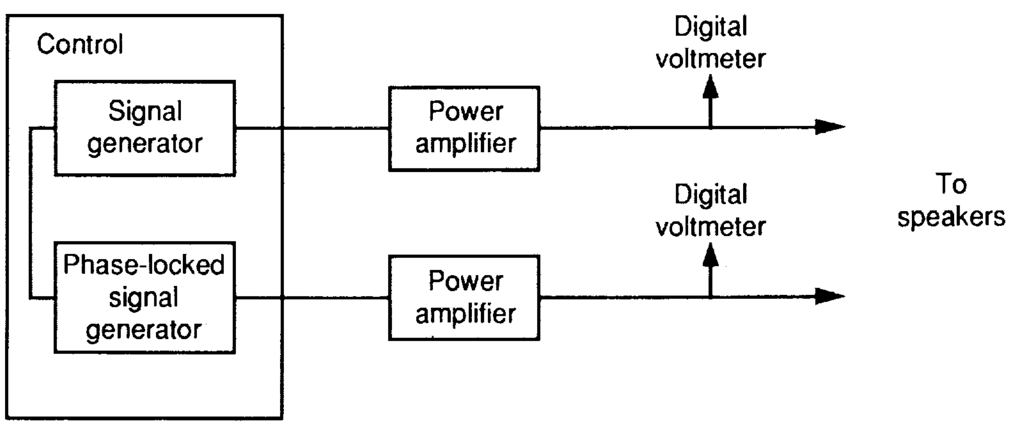
Instrumentation Block Diagram



Quadrature speaker electrical controls:

(1) Altec-Lansing audio speakers (quantity 2), model 908-8B
(2) JBL Inc. speaker drivers, model 2425A
(3) Wavetek 5-MHz phase lock generator, model 186
(4) Wavetek 20-MHz sweep generator, model 193
(5) ATO Inc. 20-MHz sweep generator, model E F74
(6) Altec-Lansing audio power amplifier (quantity 2), model 126B

Electrical Control Block Diagram



APPENDIX B
AIR PUMP ELECTRICAL CONTROLS

Electrical drive and control for pump:

(1) Boston gear ratiotrol SCR speed controller, model E33
(2) Boston gear ratiotrol variable speed dc motor (1/2 hp, 115 V dc, 1750 rpm shunt-wound)

Block Diagram

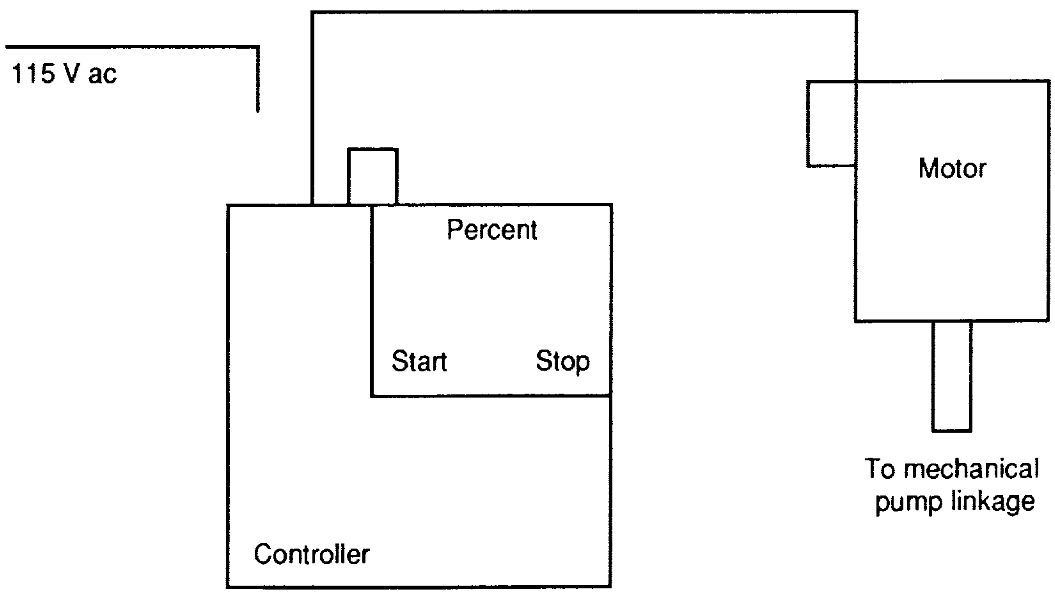


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TABLE I - NORMAL-GRAVITY TESTS OF MIXING METHODS

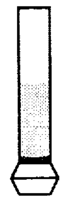
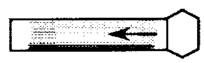
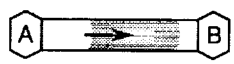
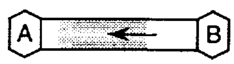
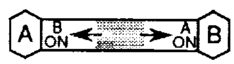
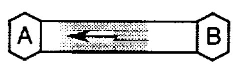
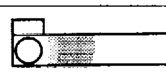
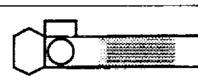
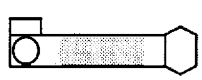
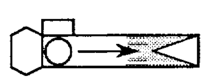
Configuration		Results
Acoustic methods		
Axial speaker on ·Vertical flame tube with two diaphragms (tested with all six tension combinations from tight-tight to loose-loose).		·Cloud rose highest in flame tubes (38 cm) with loose diaphragms on each end
·Horizontal flame tube with -steady-state operation -transient operation		·With time, fuel migrated away from speaker, but cloud did not fill tube for any of the operational sequences
		With quick transient cloud filled the tube but settled after acoustic were turned off
Twin Speakers with ·A on, B cycled		Randomly positioned fuel migrated away from speaker, then was on continuously
·A cycled, B on		
·A and B in alternating 1-Hz cycles		
·A and B on continuously		
Quadrature with ·Speakers on one end		Swirling cloud in one-third of flame tube
·Speakers on both ends		
Quadrature and one axial speaker ·All speakers at one end		·Swirling cloud in two-thirds of flame tube
·Quadrature speakers on opposite end from axial speaker		·Reduced fuel migration, but cloud did not fill flame tube
·All speakers on one end with anechoic termination on opposite end		·Fuel very quickly migrated away from speaker end

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TABLE I. - Concluded.

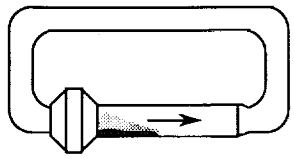
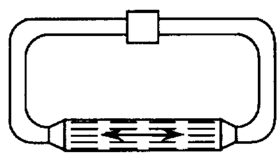
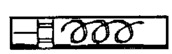
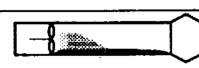
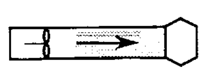
	Fans	
External		Fuel spiraled to midpoint of tube and either settled to bottom or adhered to flame tube walls
Internal •Diam, 4.8 cm; power 4.2 W •Diam, 3.0 cm; power 0.84 W •Diam, 2.4 cm; power 0.40 W		•Fuel spiraled away from fan, and no cloud was formed •No cloud formed - only swirling action in front of fan
•Test variations - forward and reverse fan operation - with and without fan cowling - fan located on and off centerline of flame tube		•None of test variations produced a sustained cloud formation
	Air pump	
•No blockage, only filters •Screen annulus •Solid blockage centered on filter •Solid blockage annulus		No fuel near the ends of flame tube; fuel was segmented into oscillating columns
	Plunger on a rod	
Mixing plunger attached to rod moved axially in flame tube		Turbulent cloud formed and quickly settled
	Fans and axial speaker	
•Fan on 1/2 sec, wait 1/2 sec, speaker on 1/2 sec		•Fan swirled small number of particles that settled out before speaker was turned on
•Speaker on 1/2 sec, wait 1/2 sec, fan on 1/2 sec		•Cloud formed with speaker on but settled before fan turned on
•Fan and speaker on 1.5 sec		•Swirling cloud was formed and fuel migrated toward speaker end

TABLE II - LOW-GRAVITY TESTS OF MIXING METHODS

Configuration	Results
Axial speaker on	
•Vertical flame tube (tested in 2.2-sec drop tower and in Learjet)	•Top of cloud reached 1/2 of tube height in 2.2 sec and slightly higher for 20-sec test, but cloud did not fill flame tube (ref. 2)
•Horizontal flame tube (tested in 2.2-sec drop tower and in Learjet)	•Cloud formed throughout flame tube, but the longer the speaker operated, the less uniform the cloud and the greater the adhesion
Plunger (tested in Learjet)	Swirling particles with severe agglomeration of fuel particles; a cloud did not fill flame tube
Fan and speaker combination (tested in the 2.2-sec drop tower)	
•Fan 1/2 sec, wait 1/2 sec, speaker on 1/2 sec	•Fan raised a small number of particles that agglomerated immediately but were broken apart when speaker was turned on
•Speaker on 1/2 sec, wait 1/2 sec, fan on 1/2 sec	•Speaker formed a cloud and fan pushed fuel toward speaker end
•Fan and speaker on 1.5 sec	•Vigorous swirling of particles migrated toward speaker end

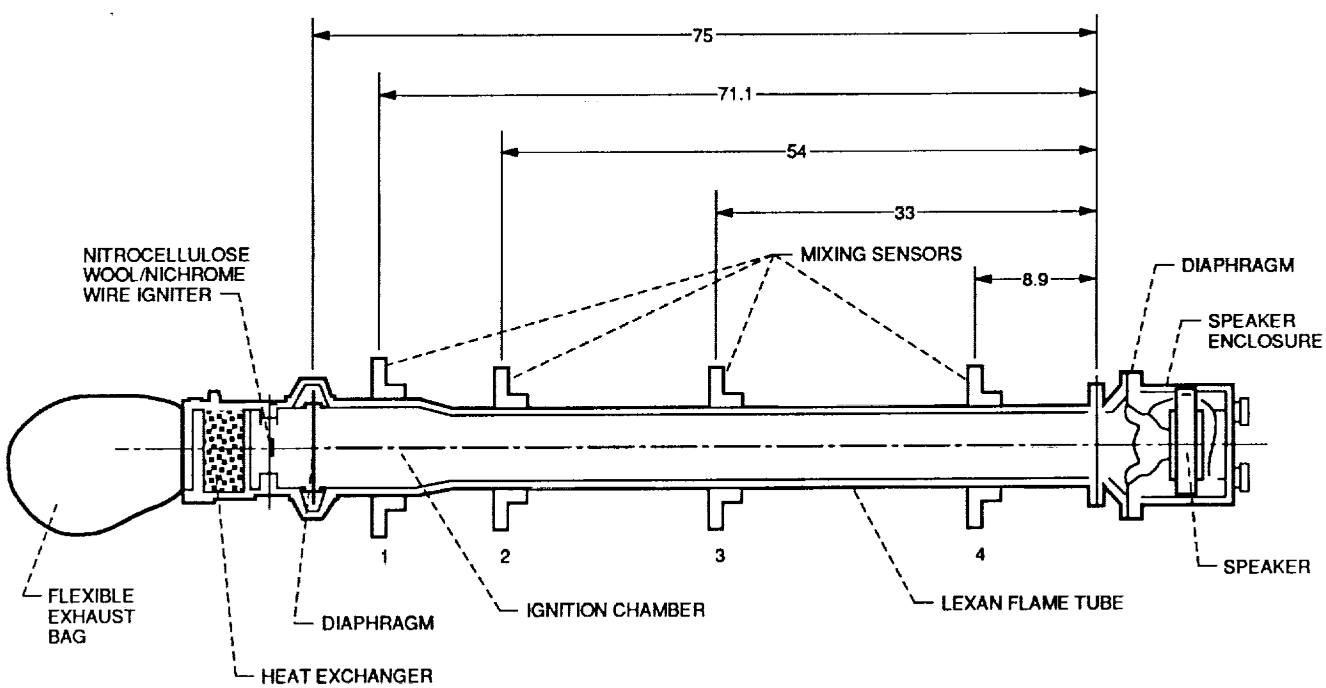


Figure 1. - Flame tube assembly with tube of 0.32 cm wall thickness and 5 cm inner diameter. All dimensions are in centimeters.

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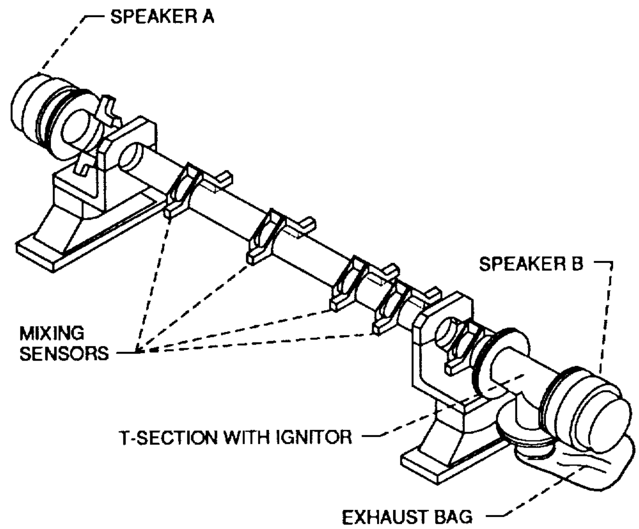

Figure 2. - Configuration for twin acoustic speaker mixing method in 75 cm flame tube.

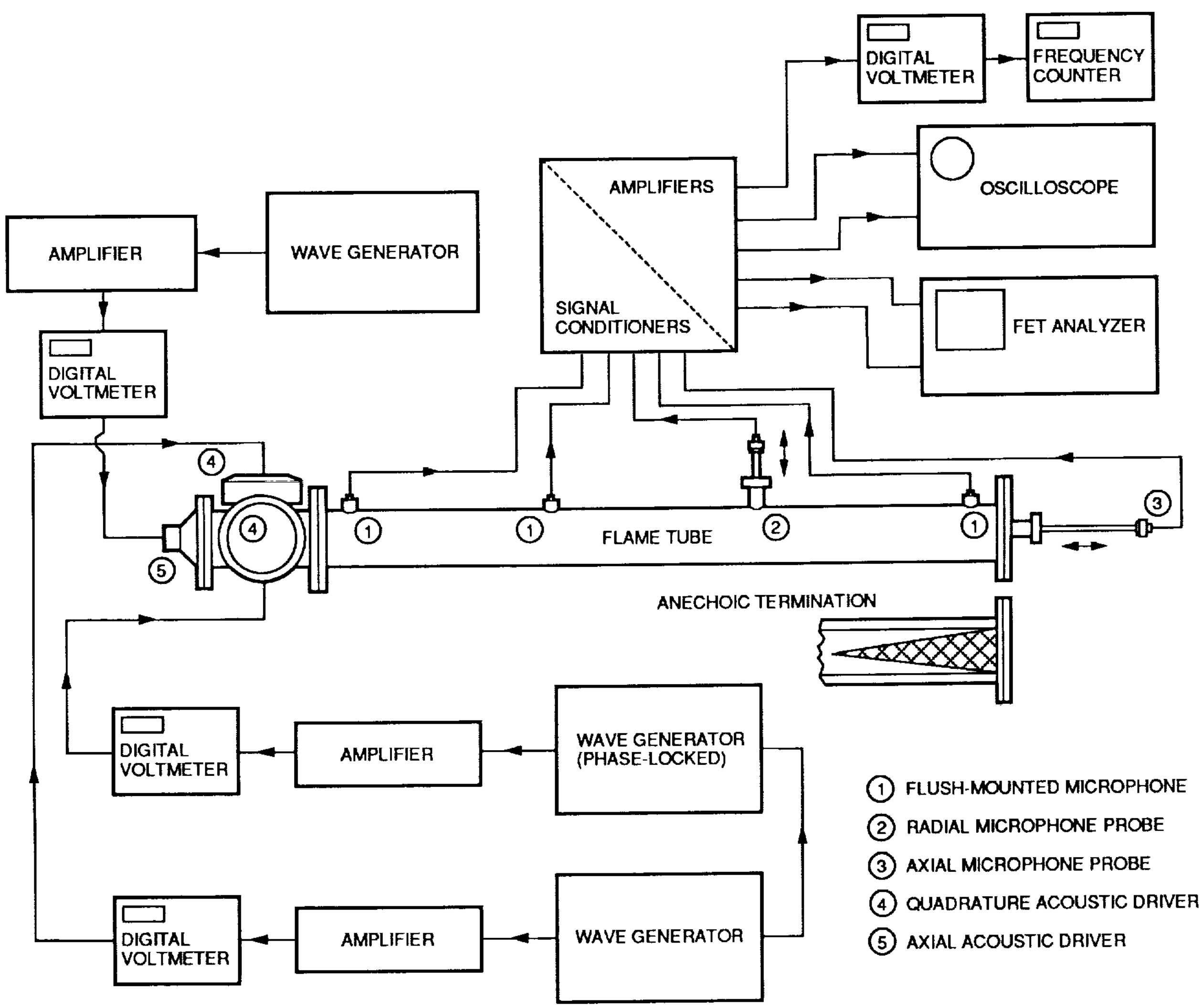

Figure 3. - Axial speaker and quadrature speaker block diagram.

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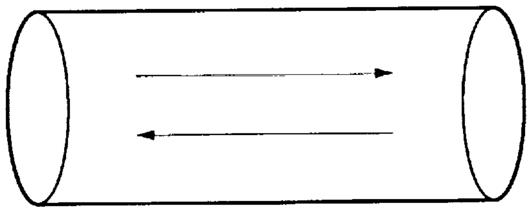
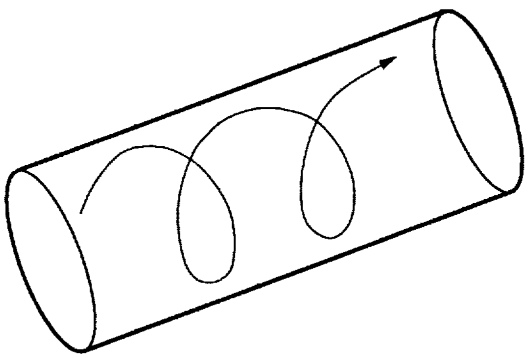
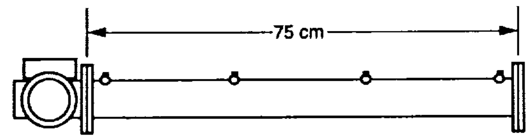


(a) Axial waves.

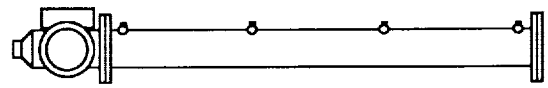


(b) Spinning waves.

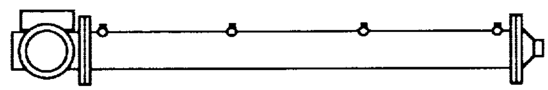
Figure 4. - Two possible types of acoustic waveforms in a cylinder.



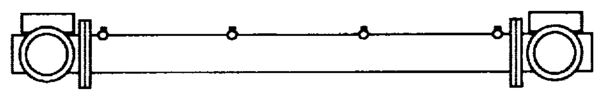
(a) Quadrature acoustic drivers.



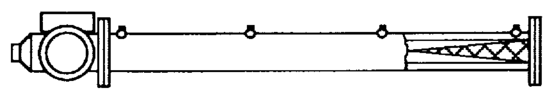
(b) Axial speaker and quadrature acoustic drivers mounted on same end of flame tube.



(c) Axial speaker and quadrature acoustic drivers mounted on opposite ends of flame tube.



(d) Double quadrature acoustic drivers.



(e) Axial speaker and quadrature acoustic drivers on one end of flame tube with anechoic termination at other end.

Figure 5. - Quadrature driver and axial speaker combinations mounted on a typical flame tube for normal gravity testing.

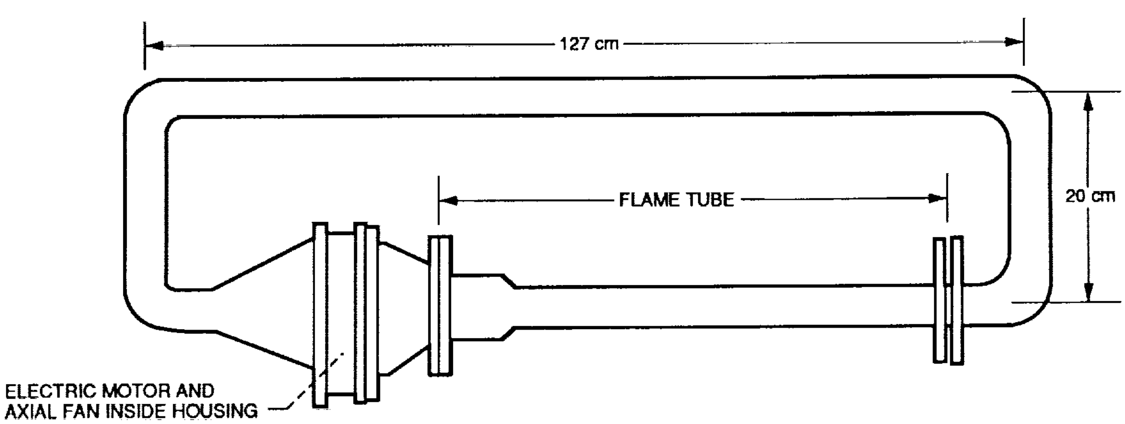


Figure 6. - Test configuration for fuel mixing in flame tube with external fan generating air flow of 3.4 m^3/min.

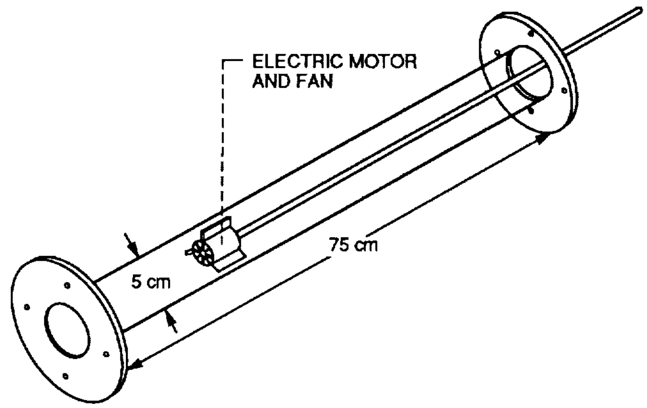


Figure 7. - Test configuration for fuel mixing with 2.4 cm diameter internal fan generating air flow of 0.16 m^3/ min in a flame tube.

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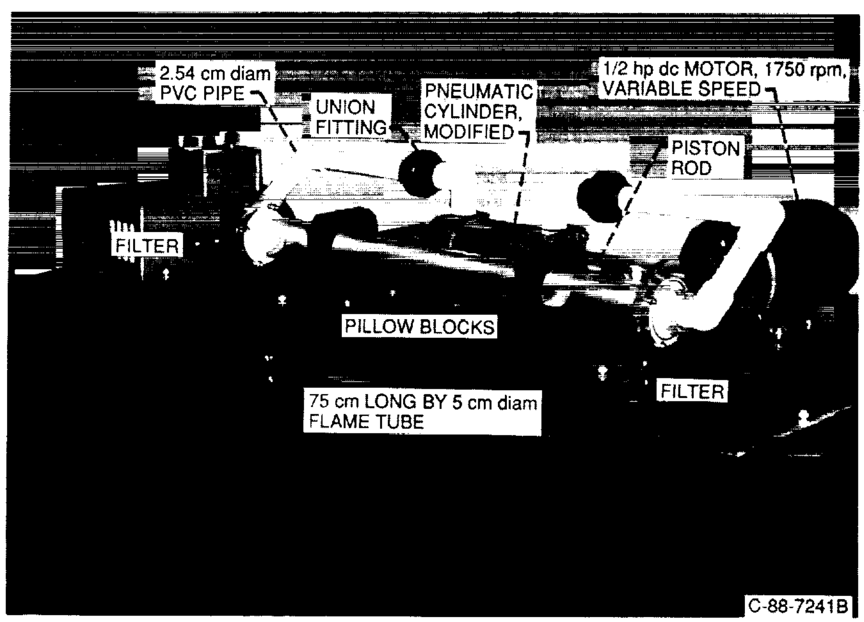

Figure 8. - Test configurations for air-pump mixing in flame tube.

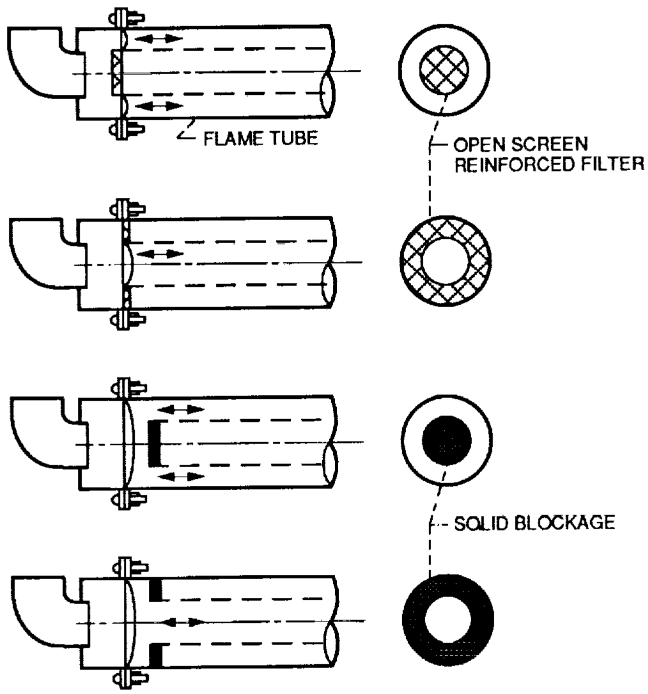

Figure 9. - Inlet and exhaust modifications to produce air flow temperature.

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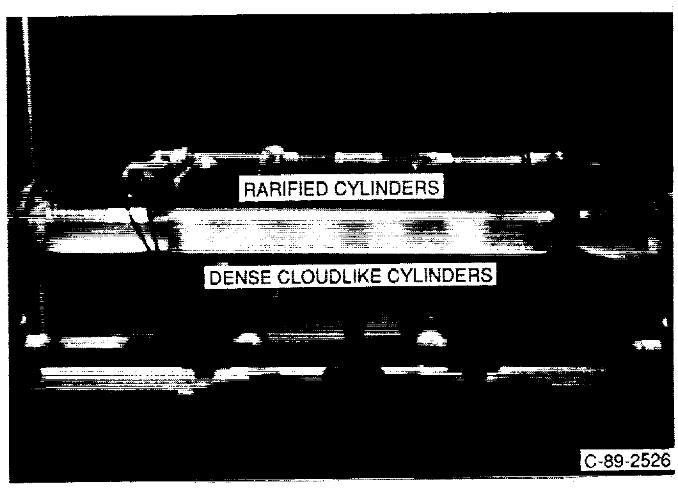

Figure 10. - Formation of fuel particles into segmented cylinders during mixing by air pump in a flame tube.

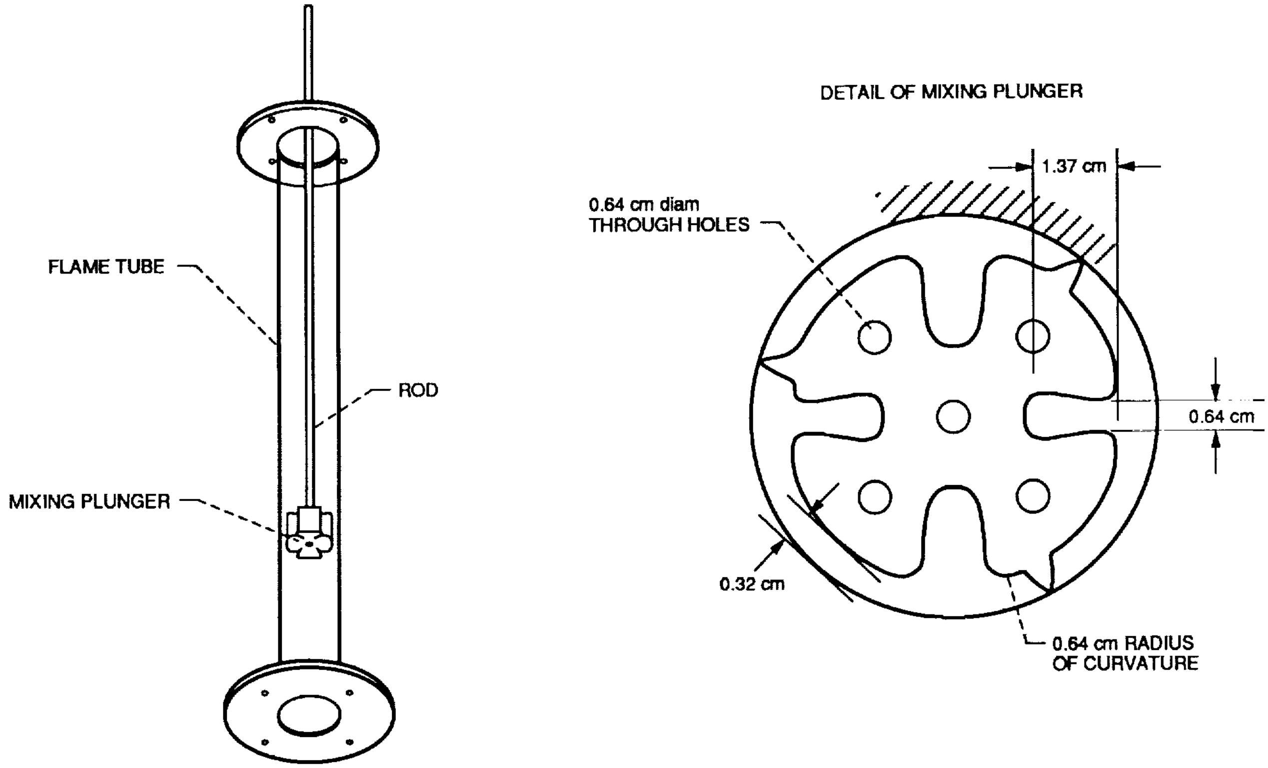

Figure 11. - Plunger configuration for mixing fuel in flame tube.

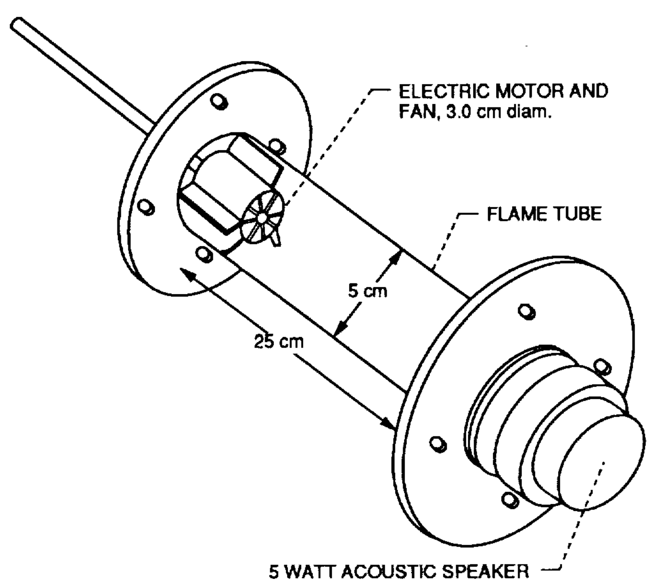

Figure 12. - Flame tube with fan and acoustic speaker mounted on opposite ends. Fan generates 0.16 m^3/min air flow.

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Report Documentation Page

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15. Supplementary Notes

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16. Abstract

The combustion of a uniform, quiescent cloud of 30-μm fuel particles in a flame tube has been proposed as a space-based, low-gravity experiment. The subject of this report is the normal- and low-gravity testing of several methods to produce such a cloud, including telescoping propeller fans, air pumps, axial and quadrature acoustical speakers, and combinations of these devices. When operated in steady state, none of the methods produced an acceptably uniform cloud (± 5 percent of the mean concetration), and voids in the cloud were clearly visible. In some cases, severe particle agglomeration was observed; however, these clusters could be broken apart by a short acoustic burst from an axially in-line speaker. Analyses and experiments reported elsewhere (briefly summarized herein) suggest that transient, acoustic mixing methods can enhance cloud uniformity while minimizing the particle agglomeration.

17. Key Words (Suggested by Author(s)): Acoustic mixing; Particle mixing; Particle mixtures; Particle clouds; Particle combustion	18. Distribution Statement: Unclassified – Unlimited, Subject Category 34

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